Gamma Ray Bursts, Supernovae and Metallicity in the Intergalactic Medium

Shlomo Dado[1], Arnon Dar[1] and A. De Rújula[2]

ABSTRACT

The mean iron abundance observed in the intracluster medium of galaxy clusters is consistent with the mean amount of iron injected in the universe per unit volume by standard supernova (SN) explosions with a rate proportional to the cosmic star-formation rate. But very little is known about field SNe at high red-shifts. Such SNe could have occurred primarily in highly obscured environments, avoiding detection. Supporting evidence for field SNe is provided by SNe associated with gamma ray bursts (GRBs) without a host galaxy and by the ratio of well localized GRBs with and without a host galaxy. A direct test of the field-SN origin of iron in the intergalactic medium would require the measurement of their rate per comoving unit volume as function of red-shift. This is feasible with IR telescopes, such as the Spitzer Space Telescope.

1. Introduction

Iron abundances in the hot intracluster medium (ICM) in galaxy clusters and in the intergalactic medium (IGM) have been known to be rather enriched: their typical value is one third of the solar one (e.g. Edge and Stewart 1991; Arnaud et al. 1992). Recent precise measurements of intracluster abundances with Beppo-SAX, Chandra and XMM-Newton have confirmed that the average metallicity throughout most of the volume of galaxy clusters is $Z \sim 0.3\, Z_{\odot}$. It has been argued that such a metallicity is several times larger than that expected from standard supernova (SN) explosions assuming standard initial mass functions (e.g., Renzini et al. 1993; Brighenti & Mathewes 1998; Loewenstein 2000; Maoz & Gal-Yam 2004). It was suggested (Scannapieco, Schneider & Ferrara 2003 and references therein) that such a puzzling iron enrichment of the ICM may be due to the production and dispersion

[1]dado@phep3.technion.ac.il, arnon@physics.technion.ac.il, dar@cern.ch.
Physics Department and Space Research Institute, Technion, Haifa 32000, Israel.

[2]Alvaro.Derujula@cern.ch; Theory Unit, CERN, 1211 Geneva 23, Switzerland.
Physics Department, Boston University, USA.

of metals from explosions of Population III stars –hypothetical, extremely massive and hot stars with virtually no metal content, believed to have existed in the early universe. These stars have been invoked to account for faint blue galaxies, and the heavy elements in quasar emission spectra, which cannot be primordial. It has also been suggested that Population III stars triggered the period of reionization (Loeb & Barkana 2001 and references therein) as inferred from the measured polarization of the cosmic microwave background radiation (Barkats et al. 2005). So far, Population III stars have not been observed[1].

In the local universe, most SN explosions take place inside ordinary galaxies. Recent near-infrared (Perez-Gonzalez et al. 2005) and radio searches for SNe have shown that they take place mostly in very dusty environments and that their rate per comoving unit volume increases sharply with red-shift z. If field SNe at large z took place mainly in dusty environments, most of them could have avoided detection. In this note we present a simple calculation which demonstrates that such SNe could have produced the iron abundance in the ICM and IGM with no need for Population III stars, provided the SNe rate per unit volume is, as expected, proportional to the star formation rate. We point out supportive evidence from the ratio of well localized gamma ray bursts (GRBs) with and without host galaxies, as well as from GRBs coincident with SNe but without a host galaxy. A direct proof of our contention that the enrichment of iron in the IGM is due to 'hostless' field supernovae (SNe not within galaxies) would require searches with IR telescopes –such as the Spitzer Space Telescope– and measurements of their rate per unit volume as function of z.

2. Iron production by ordinary Supernovae

In the simplest 'bottom-up' structure-formation models, stars form first. Subsequently, 'assisted' by dark matter, they form galaxies. Finally, galaxies 'separate from the universal expansion' to become galaxy clusters[2]. The progenitors of SNe are massive stars of short lifetime. Thus, the SN rate should follow the star formation rate. The observed rate, SFR(z), is well represented (e.g., Perez-Gonzalez et al. 2005; Schiminovich et al. 2005) by $\mathrm{SFR}(z) = \mathrm{SFR}(0)\,(1+z)^4$ for $z \leq 1$, and $\mathrm{SFR}(z) \approx \mathrm{SFR}(z=1)$ for $1 \leq z \leq 5$, see Fig. 1.

Galaxy clusters have been formed quite recently. Since star formation took place mainly during the pre-cluster stage, the IGM and ICM are expected to have similar iron abundances,

[1] Indirect evidence for the existence of Population III stars has been claimed from gravitational lensing of a high red-shift galaxy (Fosbury et al. 2003).

[2] In this picture, the ratio of baryonic to dark matter mass in galaxy clusters is the same as that in the whole universe, and the total cluster's masses are proportional to their light, as observed.

produced during the whole history of star formation. Indeed, observations indicate that most of the cluster metals were produced at $z > 1$ (e.g., Mushotzky and Loewenstein 1997; Tozzi et al. 2003). Yet, SN explosions, the main known sources of iron in the universe, take place (Maoz & Gal-Yam. 2003) both in the ICM and in clustered galaxies (mainly SNe of type Ia in elliptical galaxies, and in the CD galaxy dominating the centers of the cooling-core clusters and producing the observed central enrichment).

Supernovae of type Ia are believed to be themonuclear explosions of white dwarfs whose mass exceeds the Chandrasekhar limit, due to accretion, or to a merger. Their Fe mass yield is $\approx 0.7 M_\odot$ per SN, and their local rate is $(0.37 \pm 0.11)\, h^2\, \mathrm{SNU}$, where h is the Hubble constant H_0 in units of $100\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$ and SNU is the number of SNe per century and per a luminosity of $10^{10}\, L_{B,\odot}$ (Cappelaro et al. 1999). The progenitors of white dwarfs of mass near the Chandrasekhar limit are probably massive stars with $M < 8\, M_\odot$, whereas the progenitors of core-collapse SNe are believed to be stars more massive than $\sim 8\, M_\odot$. The observed Fe mass yield of core-collapse SNe (supernovae of types Ib/c and II) is in the range 0.0016 to $0.26\, M_\odot$ (Hamuy 2003) with a mean value $\approx (0.05 \pm 0.03)\, M_\odot$ (Elmhamdi, Chugai & Danziger 2003). Their local rate is $(0.85 \pm 0.35)\, h^2$ SNU. Thus, for $h = 0.73$, the rate of iron production per unit volume in the local universe, which follows from its luminosity density in the B band (Cross et al. 2001), $j_{_B} \approx (2.49 \pm 0.20)\, 10^8\, h\, L_{B,\odot}\, \mathrm{Mpc^{-3}}$, is:

$$\dot{M}_{Fe} \approx (0.30 \pm 0.10)\, h^2\, \mathrm{SNU}\, M_\odot\, j_{_B} \approx (0.29 \pm 0.10) \times 10^{-4}\, M_\odot\, \mathrm{Mpc^{-3}\, y^{-1}}\,. \tag{1}$$

For a SN rate proportional to the star formation rate, Eq. (1) yields an iron number density:

$$n_{_{Fe}} \approx \frac{(0.28 \pm 0.10) \times 10^{-4}\, M_\odot}{56\, m_p\, \mathrm{Mpc^3\, y}} \int \frac{\mathrm{SFR}(z)}{\mathrm{SFR}(0)}\, \frac{dt}{dz}\, dz\,. \tag{2}$$

In a standard flat universe

$$\frac{dt}{dz} = \frac{1}{H_0\, (1+z)\, \sqrt{(1+z)^3\, \Omega_M + \Omega_\Lambda}}\,, \tag{3}$$

where $H_0 = (73 \pm 2)\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$, and $\Omega_M = 0.24 \pm 0.02$ and $\Omega_\Lambda = 0.76 \pm 0.02$ are, respectively, the matter density and the density of dark energy in critical units, $\rho_c = 3\, H_0^2/8\,\pi\, G \approx (1.00 \pm 0.05) \times 10^{-29}\, \mathrm{g\, cm^{-3}}$, as inferred from the measurements of the anisotropy of the microwave background radiation (Spergel et al. 2006) with the Wilkinson Microwave Anisotropy Probe. With these parameters, Eq. (2) yields a mean density of iron nuclei in the present universe, $n_{_{Fe}} \approx (2.8 \pm 1.0) \times 10^{-12}\, \mathrm{cm^{-3}}$, where the error is dominated by the uncertainty in the rate of SNeIa. The current mean cosmic baryon density in critical units as inferred from the sky distribution of the cosmic microwave background radiation (Spergel et al. 2006) is $\Omega_b = 0.042 \pm 0.002$, resulting in a mean cosmic baryon density of $n_b = (2.52 \pm 0.2) \times 10^{-7} \mathrm{cm^{-3}}$, consistent with its inferred value from Big Bang Nucleosynthesis. The hydrogen mass fraction produced by Big Bang nucleosynthesis is, $\approx 76\% \pm 1\%$ (e.g., Peimbert et al. 2007), and has not changed much by stellar evolution. Approximately 1/6 of the baryons in galaxy clusters reside within galaxies, while 5/6 are in the ICM (e.g., Ettori 2003). Hence, the mean ratio of iron nuclei to hydrogen nuclei in the IGM is:

$$[Fe/H]_{IGM} \approx (1.22 \pm 0.3) \times 10^{-5}\,. \tag{4}$$

The relative abundance of iron to hydrogen in the Sun (Grevesse & Sauval 1998) is $[F/H]_\odot \approx (3.16 \pm 0.16) \times 10^{-5}$, and the expected mean iron abundance in the IGM from SNe, given by Eq. (4), satisfies $[Fe/H]_{IGM} \approx (0.38 \pm 0.14) \times [F/H]_\odot$, in agreement with observations.

3. Hostless GRBs

There is mounting evidence that long duration GRBs are associated with core-collapse supernova explosions (see, e.g., A. Dar 2004 and references therein). Evidence for such an association was already visible in the first discovered optical afterglow of a GRB, i.e. that of GRB 970228, but became convincing only after the measurement of its red-shift (Dar 1999; Reichart 1999; Galama et al. 2000). The first clear evidence for a GRB-SN association came from the discovery of SN1998bw in the error circle of GRB980425 by Galama et al. (1998). It was not widely accepted and was argued to be either a chance coincidence or an association between a rare type of GRB and a rare type of SN. But shortly after, evidence for a SN contribution to the late optical afterglow of an ordinary GRB (990319) was discovered by Bloom et al. (1999). The late bump in its optical afterglow, if it was produced by a bright SN akin to SN1998bw, indicated that the red-shift of the GRB/SN was less than 1. However, deep searches with HST for a host galaxy failed to detect it down to $V = 29.25 \pm 0.25$ (Fruchter et al. 2001). A galaxy at $z \sim 1$ with this observed magnitude is 7 magnitudes below L^*, the knee of the galaxy luminosity function at that red-shift. GRB 990319 was the first GRB to provide evidence for production of GRBs by field SNe.

A core collapse SNe origin of long-duration GRBs appears to be compatible with the observations (e.g., A. Dar 2004). But the afterglows of two recent GRBs, 060614 and 060505, which were located in the outskirts of nearby galaxies, did not show any evidence for an associated SN (Gal-Yam et. al. 2006; Fynbo et al. 2006). Although it is conceivable that these GRBs belong to a new class of GRBs (Gal-Yam et al. 2006), e.g., GRBs associated with 'failed' SNe, as conjectured long ago by Woosley (1993), it was pointed out by Schaefer and Xiao (2006) (see also Dado et al. 2006) that GRB 060614 looks like an ordinary GRB at a much higher red-shift, $z \sim 1.9$, as suggested by various red-shift indicators of ordinary

GRBs. The proximity of the sky position of these two GRBs to nearby galaxies could have been a chance coincidence and not a physical association. An underlying SN at red-shift $z \sim 1.9$ is too dim to be detected in the afterglow of an ordinary GRB at a red-shift $z \sim 1.9$. Discussing GRB 060614, Gal-Yam et al. (2006) responded that deep searches with the HST failed to detect a host galaxy at $z \sim 1.9$. However, if this GRB was an ordinary one, produced by a field SN at that red-shift, there would be no galaxy to be observed by the HST at its sky position.

The current ratio between the number of baryons in galaxies and in the ICM of galaxy clusters, inferred from X-ray and optical observations, is $\sim$ 5:1, e.g., Ettori (2001). Since the metallicity of the ICM of galaxy clusters is ~ 3 times less than in their galaxies, we expect the ratio of SNe which took place in the IGM to those which took place in galaxies to be roughly 2:1. Such a ratio is consistent with a rough estimate of the observed ratio of GRBs with and without a detected host galaxy: out of the 97 SWIFT GRBs which were well localized by their optical and/or radio afterglows, nearly 2/3 have no detected host galaxy, in spite of deep searches in most of them.

4. Conclusions

The simple calculation presented in this note demonstrates that no early iron enrichment of the intracluster gas by Population III stars is required, weakening the main argument implying that they once existed. To reach this conclusion, we have made the very reasonable assumption that the rates of thermonuclear and core-collapse SNe, in the gas which ended in the ICM of clusters, were proportional to the cosmic star-formation rate. Our results agree with the observed metallicities and their distribution in galaxies, the ICM and the IGM. Combined with the observed levels of the associations between (mainly long-duration) GRBs and SNe (nearly complete), as well as between GRBs and host galaxies, our results imply that nearly 2/3 of the long-duration GRBs are produced by *field* SNe. This prediction is consistent with the current data on long-duration GRBs, but deeper searches for host galaxies of well-localized long GRBs would further test it. A few observed cases of GRBs or X-ray flashes associated with SNe, but with no detected host galaxy, support our conclusion. A conclusive test of the field-SN origin of iron in the intergalactic medium would require measurements of their rate per unit volume and red-shift with IR telescopes, such as the Spitzer Space Telescope. Such searches may settle the questions of the cosmic distribution of SNe and of the need to assume the existence of a first generation of Population III stars.

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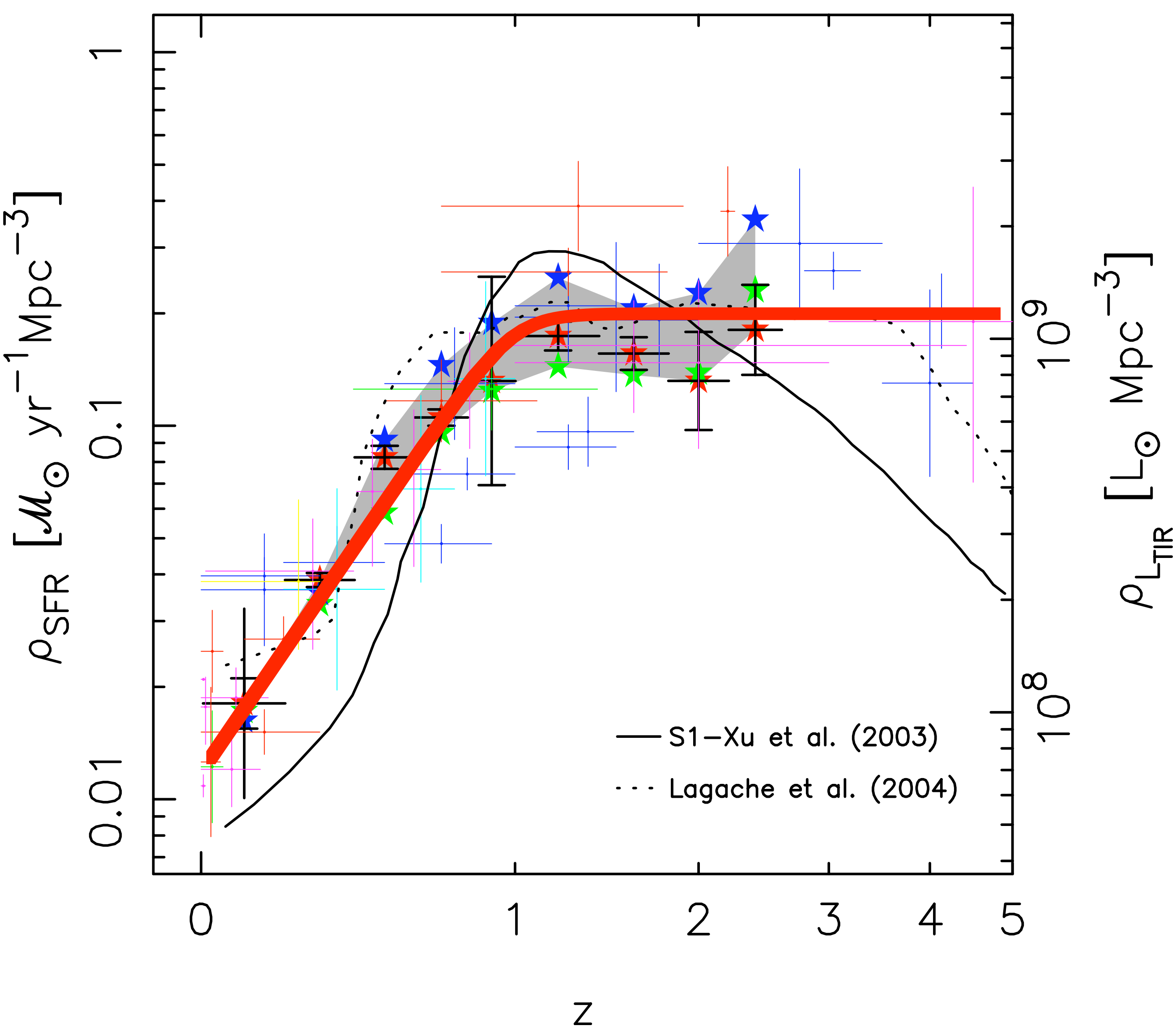

Fig. 1.— Data on the star formation rate as function of red-shift, compiled by Perez-Gonzalez et al. (2005). The thick (red) line is used in our calculations.